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Automated Detection of Individual Tree Parameters using Terrestrial Laser Scanning Data

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ABSTRACT

The National Forest Inventory aims to provide current information on forest resources for planning, management, development, and maintenance purposes, as well as quantitative and qualitative data on forest resources. Although destructive sampling is the most accurate method for obtaining tree information, it requires substantial resources, is time-consuming, and labour-intensive. This study was undertaken to compare the effectiveness of Terrestrial Laser Scanning (TLS) in extracting tree parameters in comparison to conventional methods. The results revealed a strong positive correlation between field-measured Diameter Breast Height (DBH) and manually extracted DBH from TLS point cloud data, with an r value of 1.0 and a Root Mean Square Error (RMSE) of 1.48 cm. However, the relationship between field-measured height and manually extracted height from TLS point cloud exhibited a weak correlation, with an r value of 0.70 and an RMSE value of 7.9 m. In conclusion, TLS data has a significant impact on enhancing the management and monitoring of the inventory status of tropical forests in Malaysia.

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INTRODUCTION

Forest resource information is essential for planning and managing various ecosystem services across different user levels, ranging from global political decision-making to s forest management, and from countrywide evaluations to localised measurements at various scales (Liang et al., 2019; Mohd Zaki et al., 2016). Key information includes tree attributes such as species, diameter at breast height (DBH), and tree height. To accurately estimate forest biomass, it is preferred to develop allometric equations that relate plant-part biomass components to tree diameter and/or height, as stated by (Brown S., 1997; Chave et al., 2005). This approach allows for concise estimation of forest biomass and eliminates the need for disruptive activities like forest stand destruction. Moreover, it enables the investigation of large research areas.

Remote sensing devices are valuable tools for collecting large amounts of data and acquiring reliable and consistent information about forest regions that are difficult to access. One (1) remote sensing method that can be applied is Light Detection and Ranging (LiDAR), which was introduced in the late 1990s and has provided new insights into assessing forest structure and the three-dimensional (3D) distribution of plant canopies at both plot and regional scales (Bauwens et al., 2016).

Over the past two (2) decades, TLS has been proven to be a successful approach for obtaining accurate information on tree attributes in forest sample plots. The rapid development of portable TLS systems in recent years has increased interest in their implementation in forest inventories, especially in situations where direct measurements are expensive or impractical (Abegg et al., 2017). Several studies have demonstrated the application of TLS in improving the tropical forest inventories by focusing on tree height, diameter at breast height (DBH), and Above-Ground Biomass (ABG) estimation (S. M. Beyene et al., 2020; Prasada et al., 2016; Rahman et al., 2017). TLS data, in general, provides valuable information about forest ground structure and enables automatic extraction of tree height and DBH, offering significant advantages in estimating forest AGB.

Most researchers (Arkerblom et al., 2017; Calders et al., 2015; Tian et al., 2019) have primarily focused on studying single species in deciduous and coniferous forests, with limited research on detecting forest attributes in general also, conducted in obtaining the forest inventory information in less dense forest areas, where species diversity is relatively low compared to tropical forest. Therefore, the aim of this study was to conduct at *Dipterocarp* and *Non- Dipterocarp* Forests to compare the effectiveness of TLS in extracting tree parameters with the conventional methods. This paper will outline the process of collecting tree inventory data in the area and describe how single tree parameters are derived from TLS and compared to the others, this study was conducted at large area with various species. Material and Methods

RESEARCH METHODOLOGY

For this study, the data was collected from two (2) specific areas within Forest Research Institute of Malaysia (FRIM); the Dipterocarp Arboretum and the *Non-Dipterocarp* Arboretum, as shown in Fig 1. The *Dipterocarp* Arboretum was established in 1929 and houses a collection of *Dipterocarpaceae* species. On the other hand, the *Non-Dipterocarp* Arboretum comprises trees from *non-Dipterocarpaceae* families. Currently, the Dipterocarp Arboretum contains 120 species, while the *Non-Dipterocarp* Arboretum boasts 169 species from 45 families.

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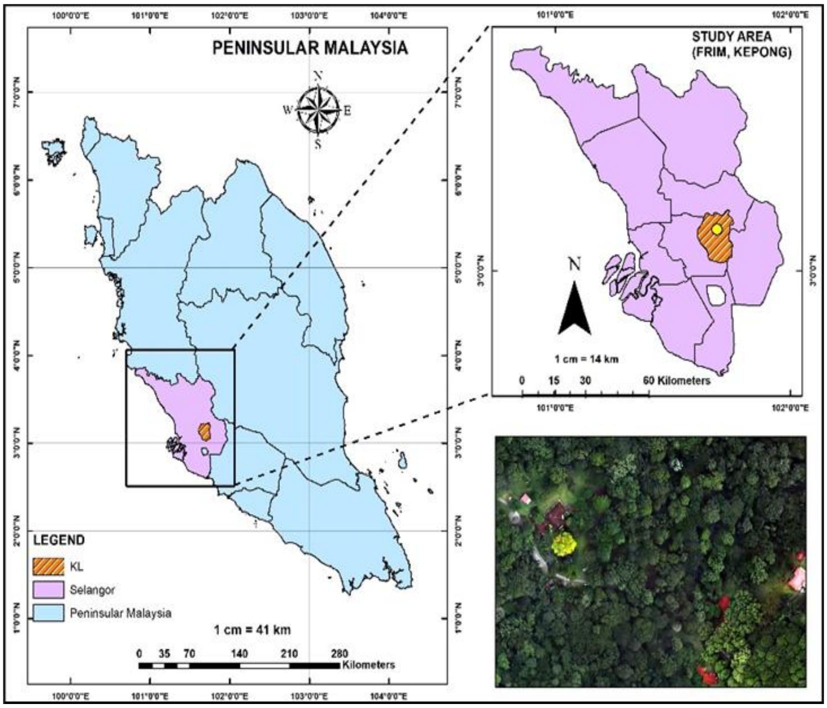

Fig. 1. Map of study area

Source: Authors (2024)

Fig 2. provides a detailed discussion of each stage of the methodology. The methodology employed in this study aimed to obtain and compare tree parameters using both conventional methods and TLS measurements. It involved data acquisition in the field, data processing, and subsequent statistical analysis.

The first step was the data acquisition phase, where tree individual height and DBH were measured using both conventional methods and TLS. The TLS method generated point cloud data, which was crucial in reconstructing individual trees and estimating their parameters and locations.

The second step involved data processing. The raw point cloud data was processed to extract tree information, specifically height and DBH of each individual tree. However, it's worth noting that registration and georeferencing of the point cloud data were not performed based on the data acquisition phase. This due to the method apply when collecting the data on the site, where the scanning point is closed with each other and the targeting point for the tree for each plot still visible to see. Finally, statistical analysis was conducted to assess the correlation between the obtained parameters.

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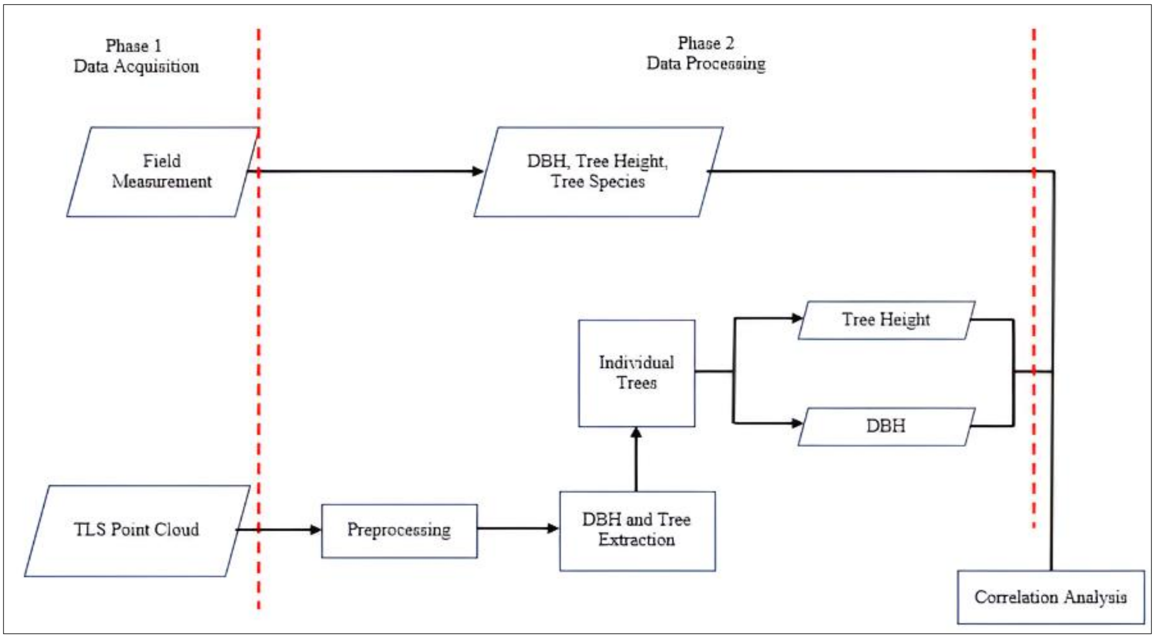

Fig. 2. Flow chart of methodology

Source: Authors (2024)

Field Data Collection

The plot dimensions measure 25 m x 25 m and consists of 24 subplots, as depicted in Fig 3. These subplots will be utilised for data collection through the use of Terrestrial Laser Scanning (TLS) in the present study. Previous research conducted by Arkerblom et al., (2017) and Raumonen et al., (2013) has emphasised the importance of conducting a more comprehensive examination involving larger field measurements. This approach allows for the recording of a greater number of tree species, leading to improved accuracy and the ability to generate more generalised.

For each tree within the plot, biometric data such as tree height, Diameter at Breast Height (DBH), coordinates, and scientific species names were recorded and entered into a Microsoft Excel table. These data were utilised to calculate the Above-Ground biomass (AGB) of the trees using conventional methodologies. The DBH measurements were taken at a height of 1.3 meters above the ground using a diameter tape. To ensure consistency across all trees, a standardised stick measuring 1.3 meters was employed to indicate the DBH position. This measurement was obtained either above the buttress or any trunk deformities present in the case of buttress trees or trees with deformities (Chave et al., 2014). Additionally, the height of the trees was measured using a laser range finder in meters (Leica DISTO D510). Due to the overlapping canopy structures, it was impossible to distinguish the true crown of individual trees during the tree height measurements.

When utilising TLS (Terrestrial Laser Scanning) for point cloud data acquisitions, there are generally two (2) methodologies employed, contingent upon the intended objective. Within the designated sample plot, trees exhibiting a Diameter at Breast Height (DBH) of less than 10 cm were specifically identified through markings to differentiate them from other trees. These marked trees are subsequently scanned alongside the encompassing area in order to quantify a range of tree parameters, including DBH, height,

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crown diameter, and other relevant metrics. By collecting point clouds from various positions within the sample plot, the three-dimensional (3D) structure of the trees can be accurately ascertained.

D1	D2	D3	D4	D5	D6
C1	C2	C3	C4	C5	C6
B1	B2	B3	B4	B5	B6
A1	A2	A3	A4	A5	A6

Field data collection: subplot ☐

Fig. 3. Location of the test site and subplot position

Source: Authors (2024)

TLS Instrument

The RIEGL VZ-400 terrestrial laser scanner, manufactured by RIEGL Laser Measurement Systems GmbH, is a commercial scanner known for its higher accuracy, longer range, and more powerful data acquisition capabilities (Wang, Li, et al., 2019). This scanner has been utilised in various studies involving three-dimensional (3D) modelling (Decuyper et al., 2018; Lau et al., 2018) and data acquisition (Wilkes et al., 2017). It features a divergence of 0.35mrad (Wilkes et al., 2017) and offers a beam scan range of 360° in the azimuth and 100° in the zenith direction. Table 1 displays the Riegl VZ-400 scanner and its corresponding specifications, as employed in the present study.

All the data were scanned using the RIEGL VZ-400 terrestrial laser scanner, manufactured by RIEGL Laser Measurement Systems GmbH. The scanner data was registered using the RiSCAN PRO software, provided by RIEGL. RiSCAN PRO is a robust software suite developed by RIEGL for processing and analysing data. It enables users to import, visualise, and edit point clouds generated by the scanners. In the context of forest applications, this software provides valuable information about the forest structure. It can extract and analyse individual tree data from point clouds, including tree height, diameter, and canopy volume. The software is applicable for both detailed structural assessments and large-scale monitoring and planning.

TLS Plot Setup

The success of tree detection varied depending on factors such as distance from the scan center, forest density, field topography, and understory layers (Pazhouhan et al., 2017). As a result, it is crucial to properly set up the Terrestrial Laser Scanner (TLS) before conducting the actual scanning. In this particular study, the TLS will be mounted on a tripod to ensure its stability at an elevated position. This setup can improve the accuracy of the laser beam emitted by the TLS, reducing errors like occlusion and blocking when reaching the surface of tree structures. Consequently, several aspects need to be taken into consideration, including plot identification, tree labelling, and clearing of undergrowth.

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When applying TLS (Terrestrial Laser Scanning) to collections of point cloud data, there are generally two (2) approaches that can be taken, depending on the specific objective being pursued. In this study, trees with a diameter at breast height (DBH) of ≥ 10 cm within the sample plot were identified and marked to distinguish them from other trees that were also scanned within and around the sample area. This allowed for the measurement of various tree parameters such as DBH, height, volume, etc. The point clouds acquired from multiple positions within the sample plot facilitated the determination of the three-dimensional (3D) structure of the trees.

There are two (2) types of scanning methods: single scan and multiple scan (Bienert et al., 2018). The single scan method involves recording only one (1) side of the trees and employing a single location scan in the centre of the plot. However, due to the specific characteristics of the location, a single scan approach with a limited scanning range was utilised in this study. Additionally, long range scanning was implemented outside of the plot to enhance the three-dimensional (3D) representation of the trees and improve observations of canopy height. The determination of the scanning range was based on the capabilities of the Terrestrial Laser Scanner (TLS) and the dimensions of the plot.

The central plot serves as the reference point within the sample plot, aiding in the registration of the outer scanning positions and providing guidance for the installation of the external scanner position (G. K. Beyene, 2019). It must be carefully selected after identifying the sample plot, considering factors such as slope, spacing, and undergrowth. This ensures that adjustments are made to accommodate tree stems and undergrowth, such as bushes, shrubs, and props, in order to prevent occlusion or, at the very least, minimise its effects. This is particularly important when conducting TLS levelling on uneven terrain.

Table 1. Terrestrial Laser Scanning Specification

Technical Specification (RIEGL VZ-400)	
Laser Wavelength (nm)	1550
Min. Range (m)	1.5
Mxm. Range (m)	600
Horizontal field of view	0° – 360°
Vertical field of view	100° (30-130) °
Pattern	Panorama - 40
Accuracy (mm)	5mm
Precision	3mm
Peak pulse frequency	300 kHz
Weight	9.6kg (approximate)

Source: Authors (2024)

Extraction of Tree Parameters

Individual trees were manually extracted from registered point clouds obtained from the Terrestrial Laser Scanner (TLS) using RiSCAN PRO software. From 24 plots, A total of. 200 trees were extracted from 24 plots, focusing on trees with dense point clouds that were clearly visible to the laser beams and not intertwined with other trees. The TLS data processing involved the elimination of multiple scans, background vegetation, and unrelated vegetation until point clouds specific to individual trees were generated. Once the point clouds from all the single scanning positions were registered, the manual extraction process began. Using RiSCAN PRO's measuring tool (as shown in Fig. 5.), the Diameter at Breast Height (DBH) and height of each tree were measured.

To enhance the visibility of the tree tags, the point clouds were visualised using either 3D linear scaling or true colour representation. The point cloud was presented in a top-view perspective, and the selection

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tool in RISCAN PRO software was employed to identify all the point clouds associated with a specific tree. Due to the overlapping nature of tree canopies in the study area, the selected point cloud encompassed crowns from neighbouring trees. The point clouds originating from nearby trees and undergrowth were subsequently removed to accurately depict the target tree. The intricate structural complexity of forests posed a challenge in distinguishing individual tree crowns due to substantial overlap. Consequently, TLS scanners continue to represent a technological obstacle in this regard.

When discussing the extraction of trees, it is important to consider two (2) distinct types of errors: type I and type II. Type I errors arise when trees are not correctly identified due to either partial or complete obstruction of the stems. Conversely, type II errors occur when a tree is incorrectly labelled as a result of a false detection (Maas et al., 2008). It should be noted, however, that in the present study, type II errors were effectively eliminated given the absence of any barriers within the research area, thereby facilitating accurate labelling of the trees.

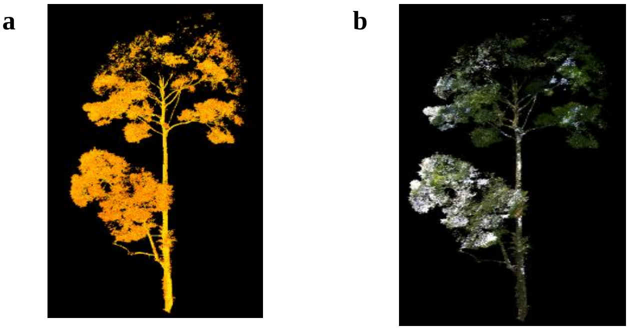

Fig. 5. Single tree extraction using: (a) Single colour; and (b) True colour.

Source: Authors (2024)

RESULTS AND DISCUSSION

Tree Species Distribution

In estimating Above-Ground Biomass (AGB) and carbon stock, it is crucial to consider the tree species involved as each species possesses a unique wood density value. The diversity of tree species within a specific research area contributes to the variability of AGB values, making it an important indicator of carbon cycling and climate change in that particular region. In the arboretum area under study, the dominant species belongs to the *Dipterocarpaceae* family, accounting for 63% of the tree composition. Additionally, there are other species from various families, including *Gentianaceae* (9%), *Anacardiaceae* (2%), *Malvaceae* (2%), and *Meliaceae* (2%), while the remaining species make up 1% of the composition. Although the study region may not be extensive, the presence of approximately 100 tree species within the *Dipterocarpaceae* family alone showcases a significant species diversity within the area.

Tree Detection and Accuracy Assessment

One (1) of the main objectives of the study was assess the accuracy of tree detection from point cloud data by comparing manually recognised trees per plot with field observations.

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In total, 200 trees were measured in the field across 24 plots, and the TLS technology successfully extracted and scanned all of these trees. However, some trees were excluded from further analysis due to missing species identification, measurements taken outside of the designated plot area, and outliers resulting from errors in manual tree recording. As a result, a total of 182 trees remained for further analysis. A comprehensive summary of the detailed extraction per plot can be found in Table 2.

Table 2. Trees extracted from TLS point clouds

Plot	Field Recorded	TLS Derived	Extraction %	Missing Trees	Plot	Field Recorded	TLS Derived	Extraction %	Missing Trees
1	10	10	100	0	***13***	8	8	100	0
2	11	11	100	0	***14***	9	9	100	0
3	9	9	100	0	***15***	6	6	100	0
4	8	8	100	0	***16***	7	7	100	0
5	11	11	100	0	***17***	6	6	100	0
6	11	11	100	0	***18***	7	7	100	0
7	10	10	100	0	***19***	8	8	100	0
8	7	7	100	0	***20***	7	7	100	0
9	12	12	100	0	**21**	8	8	100	0
10	8	8	100	0	***22***	9	9	100	0
11	7	7	100	0	***23***	8	8	100	0
12	6	6	100	0	***24***	7	7	100	0
No of plots		Total Trees	TLS derived		Missing Trees		TLS derived %		Missing %
24		200	200		0		100		0

Source: Authors (2024)

A descriptive statistic (Table 3.) was conducted to examine the relationship between mean, and standard deviation of DBH_{field} (mean = 61.0, SD = 25.9), DBH_{TLS} (mean = 60.9, SD = 25.9), HT_{field} (mean = 22.2, SD = 7.7) and HT_{TLS} (mean = 28.5, SD = 9.0) as presented in Table 3. The results indicated a high correlation between DBH measurements obtained through the conventional method and those derived from TLS point cloud data using RiSCAN PRO software. However, for height measurements, the correlation between these two (2) methods is not as strong as for DBH, although it is still considered acceptable for further analysis.

Table 3. Overall descriptive statistics of DBH and tree height.

	N	Minimum	Maximum	Mean	Std. Deviation
DBH_{field} (cm)	182	20.7	128.0	61.0	25.9
DBH_{TLS} (cm)	182	20.8	124.7	60.9	25.9
HT_{field} (m)	182	6.2	35.8	22.2	7.7
HT_{TLS} (m)	182	9.1	46.7	28.5	9.0

Source: Authors (2024)

The results of the normality test reveal that the data is not normally distributed, suggesting the need for Spearman's correlation analysis. The results of the Spearman's test are summarised in Table 4. The correlation analysis aimed to examine the relationship between the levels of DBH_{field}, $DBH_{TLS,}$ HT_{field} and HT_{TLS}. The analysis revealed strong positive and significant correlations between DBH_{field} and DBH_{TLS}, with a correlation coefficient of $r_s = 0.998$ (n = 182, $p < 0.001$). Similarly, there was a significant positive correlation between HT_{field} and HT_{TLS}, with a correlation coefficient of $r_s = 0.849$ (n = 182, $p < 0.001$).

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Table 4. Spearman's Correlation between tree parameters

		DBH_{field} (cm)	DBH_{TLS} (cm)	HT_{field} (m)	HT_{TLS} (m)
DBH_{field} (cm)	Correlation Coefficient	1.000	.998**	.713**	.686**
	Sig. (2-tailed)	.	.000	.000	.000
	N	182	182	182	182
DBH_{TLS} (cm)	Correlation Coefficient	.998**	1.000	.712**	.685**
	Sig. (2-tailed)	.000	.	.000	.000
	N	182	182	182	182
HT_{field} (m)	Correlation Coefficient	.713**	.712**	1.000	.849**
	Sig. (2-tailed)	.000	.000	.	.000
	N	182	182	182	182
HT_{TLS}(m)	Correlation Coefficient	.686**	.685**	.849**	1.000
	Sig. (2-tailed)	.000	.000	.000	.
	N	182	182	182	182

Source: Authors (2024)

Diameter Breast Height and Tree Height Accuracy Assessment

In Fig 6., a linear regression was conducted to illustrate the relationship between field-measured DBH_{field} and DBH_{TLS}, as well as HT_{field} and HT_{TLS} estimations. The results showed that the DBH_{TLS} measurements had no significant impact on the model inferences for all matched trees, as the linear regression fit model closely aligned with the one-to-one line. The relationship between field measured DBH and manually extracted DBH from the TLS point cloud exhibited a high R^2 value of 1.0, indicating a strong correlation. The RMSE value was reported as 1.48 cm (equivalent to 67.55 %), suggesting a relatively small deviation. The statistical test revealed that there was no statistically significant difference between the DBH obtained in the field and the TLS point cloud data. Considering the study region's conditions, which lacked extensive tree undergrowth and therefore minimised occlusion, no significant issues were encountered in measuring the DBH.

The correlation analysis showed a lower correlation between HT_{field} and HT_{TLS}, with a coefficient of determination (R2) of 0.70. The height measurement also had an RMSE value of 7.9 meters, equivalent to 12.65% of the mean height. The relationship between the height parameters obtained from both methods is summarised in Table 7. In order to accurately measure the tree height, the height measuring apparatus used in this study required a clear view of the treetop and base. However, in the study area, various factors such as occlusion caused by neighbouring tree crowns, the presence of large tree crowns, and limited observation positions, restricted the visibility of treetops and their bases. Consequently, errors were encountered in measuring tree height in the field. Furthermore, since the study area is located within a rainforest stand, it was challenging to measure tree height by visually identifying treetops using the standard method employed in this study.

Table 5. Relationship between parameter from field measured and TLS measured.

				RMSE		
Parameter	*No. of Tree*	R^2	*R*	*(cm)*	*%*	*Bias (cm)*
DBH	182	1.0	1.0	1.48	67.55	0.06
Height	182	0.71	0.84	7.90	12.65	-6.22

Source: Authors (2024)

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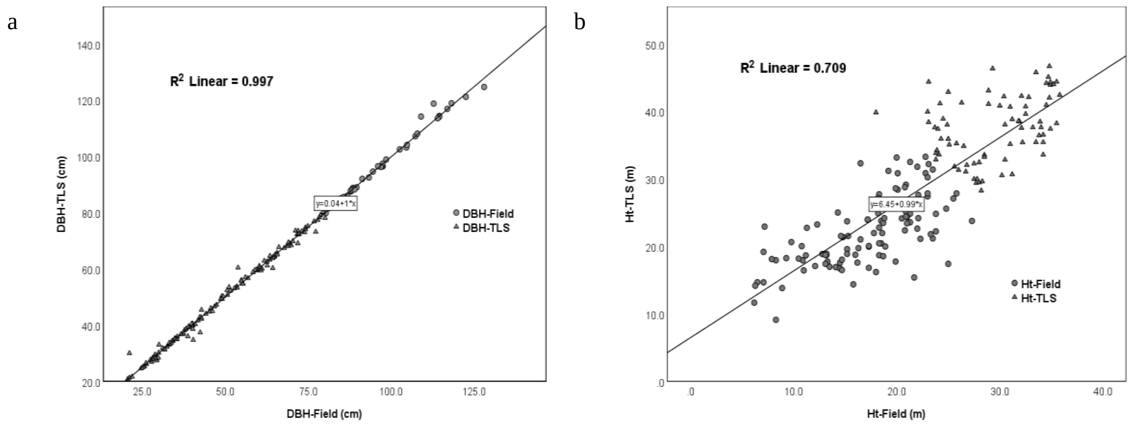

Fig.6. Scatter Plot a) DBHfield and DBHTLS b) HTfield and HTTLS

Source: Authors (2024)

Extraction of Tree

In the field, TLS successfully measured 200 trees from approximately a hundred species belonging to the dipterocarp and non-dipterocarp families. These trees were manually extracted for further analysis. However, 18 trees had to be removed from the dataset due to various reasons, including missing tree IDs, outliers, and trees located outside of the designated subplots. In this study, a single scan approach with a short scanning range was employed within the plot, supplemented by long-range scanning outside of the plot. This combination aimed to improve the 3D representation of the trees and enable accurate observation of canopy height. For the long-range scanning, TLS points were positioned at various angles along the outer perimeter of the plot, covering a distance of approximately 300 m to 400 m. This method enhanced the accuracy of tree scanning and ensured the successful capture of all sample trees in the study. The efficacy of TLS is influenced by the relatively less dense forest condition in the study area, as well as the sparse undergrowth, which reduces occlusion issues. Occlusion, caused by objects casting shadows on each other, can limit the effectiveness of TLS measurements, as noted by (Abegg et al., 2017). To address this challenge, previous studies such as Danson et al., 2007; Hosoi & Omasa, 2007; and Strahler et al., 2008 have explored strategies to overcome occlusion, including using Multiple Scans (MS) across the plot instead of a single scan (SS) at the centre or employing quantitative techniques.

Several studies have explored the application of TLS in dense tropical forests. For example, Beyene et al. (2020), Prasada et al. (2016), and Rahman et al. (2017) have estimated Above-GroundB (AGB) using tree parameters obtained from TLS. Ferraz et al., (2016) focused on predicting biophysical variables using individual tree crowns (ITC) derived from TLS data. Decuyper et al., (2018) compared the 3D structure of forests between conventional methods and TLS, while Wassihun et al., (2019) investigated the relationship between forest stand density and AGB. Direct measurements in tropical forests pose challenges due to the complexity of tree structure, crown structure, and their sizes, leading to issues such as occlusion., Occlusion is the most common challenge encountered when applying TLS in tropical forests, occurs when objects within the forest block the scanner's line of sight. To mitigate this, researchers have suggested placing the TLS scanner in areas without understory vegetation or adopting flexible positioning to capture detailed information about branches within the canopy (Lau et al., 2018). Previous studies have demonstrated high accuracy in tree detection within tropical forests using TLS. For instance, Beyene et al. (2020) achieved an overall extraction percentage of 95%, while Wassihun et al. (2019) reported a detection accuracy of 82.77% for individual trees using LiDAR in forested areas.

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Diameter Breast Height Measurement

DBH is a widely used and crucial field measurement in forest inventories. It has been found to be a strong predictor of Above-Ground Biomass (AGB) for forest sites, with little additional improvement when incorporating height as an extra parameter (Calders et al., 2015; Wang, Gan, et al., 2019). In this study, the diameter of each tree was measured using a diameter tape at a height of 1.3 meters above the ground, considering trees with a diameter ≥ 10 cm. The DBH measurements were manually recorded using the RiSCAN PRO software. The accuracy and efficiency of DBH measurement in the field can be influenced by various factors, including the measurement method, TLS equipment used, forest conditions, and tree size. Despite the relatively lower density of the studied forest compared to other tropical forests, occlusion can still occur. Occlusion refers to objects casting shadows on each other, thereby obstructing the view of the TLS device and obscuring parts of the objects of interest (Abegg et al., 2017). Trees surrounded by dense undergrowth can pose challenges for manual measurements in this study. Therefore, it is necessary to remove noise and accurately determine the true value of DBH for each tree. Removing unnecessary tree, facilitates the measurement of DBH and allows for the identification of point clouds specific to individual trees, which provides accurate values. The study's results demonstrate a strong correlation between field-measured DBH and manually extracted TLS DBH, with no significant differences between the two (2) methods. The relationship between the two (2) approaches is characterised by a high R^2 value of 1.0 and an RMSE value of 1.48 cm, indicating the effectiveness of TLS in measuring DBH. The observed relationship between field-measured and TLS-measured DBH in this study is higher compared to the results of other studies conducted in tropical forests in Malaysia. For example, Rahman et al. (2017) reported an R^2 value of 0.969 and an RMSE value of 0.062 cm, Bazezew et al., (2018) reported an R^2 value of 0.98 and an RMSE value of 1.23 cm, and Beyene et al. (2020) reported an R^2 value of 0.98 and an RMSE value of 1.37 cm. These findings highlight the strong agreement between the field and TLS measurements of DBH in the present study.

Height Measurement

Tree height is an important factor in estimating Above-Ground Biomass (AGB), and previous studies, such as Ioki et al., (2014) have shown that AGB in tropical environments can be approximated using height-related statistical factors. Additionally, height plays a crucial role in studying the life history of trees in tropical forests, considering factors such as tree height, crown size, and canopy density (Zulkiflee et al., 2011). In tropical forests, tree crowns tend to be large, which poses challenges in accurately determining the true top of a tree. This difficulty in locating the tree's actual peak is one (1) of the main sources of occlusion, caused by overlapping crowns in the upper canopy of the trees, as mentioned by Prasada et al. (2016). Furthermore, the focus of TLS returns is generally on the lower canopy, limiting the evaluation of upper crown structure and accurate measurement of tree heights, as noted by Wassihun et al. (2019). These factors contribute to the complexities and limitations associated with measuring tree height in tropical forests.

In this study, was measured in the field using a distometer. However, accurately determining the true top of the tree proved challenging, even in a less dense forest environment, due to the size and overlapping nature of the tree canopies. For tree height measurement from the point cloud data, the distance measuring tool in RiSCAN PRO software and manual measurement were employed. The overlapping crowns posed difficulties in determining the height of individual trees, and it required time to identify the relevant point cloud data for each tree. To facilitate this process, it was recommended to assign a single colour to each tree for classification purposes.

The result of this study showed a low correlation between field measured height and TLS measured height, with an R2 value of 0.71 and an RMSE value of 7.49 cm. This indicates that the manual extraction of tree height from 3D point cloud data provides a reasonable estimate. Similar findings were reported by

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Rahman et al. (2017) with an R^2 value of 0.62 and an RMSE value of 7.10 cm, and by Prasada et al. (2016) with an R^2 value of 0.77. However, Beyene et al., (2020) demonstrated a good linear fit with an R^2 value of 0.86 when comparing the TLS height to the reference tree height measured using ALS. It is important to note that the bias in height measurement tends to be larger for tall trees in dense forests, as stated by Mohd Zaki & Abd Latif, (2017). This is due to the less defined treetops and the challenges posed by dense canopy cover.

CONCLUSION

The main objective of this study was to compare the effectiveness of TLS in extracting tree parameter for *dipterocarp* and *non-dipterocarp* tree species, as compared to field measurements. TLS data were acquired using a single scan approach with a short scanning range and supplemented by a few long-range scans beyond the plot. Due to the study area being a less dense forest, TLS point cloud was utilised to manually detect and extract tree parameters using RiSCAN PRO software. The results showed that TLS achieved a high level of accuracy in detecting all sample trees in the less dense forest. The comparison between TLS detection and field measurements indicated that TLS can accurately measure tree attributes such as DBH and height. The relationship between field-measured DBH and manually extracted DBH from TLS point cloud showed a high correlation. However, the relationship between field-measured height and manually extracted height from TLS point cloud showed a lower correlation, mainly due to the difficulty in obtaining a clear perspective of the treetop.

For future research endeavours, it is worth noting that TLS holds promise for the identification of supplementary tree parameters that can be utilised in the estimation of Above-Ground Biomass (AGB) and carbon stock. These parameters include crown diameter, tree volume, and canopy volume. Additionally, it is advised to integrate data obtained from ALS (Airborne Laser Scanning) in order to address the difficulties associated with height measurement. Furthermore, it is crucial to acknowledge that the findings derived from (TLS) were acquired within a tropical forest that exhibited a lower level of density. Therefore, it is plausible that the results may vary when applied to a typical tropical forest stand with a higher degree of canopy density. However, the application of Terrestrial Laser Scanning (TLS) for studying tropical forests is highly comprehensive. This is attributed to the intricate and dense nature of these forest ecosystems. By employing TLS technology, numerous advantages can be derived, including the reduction of time, labour, and cost associated with forest analyses.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

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AUTHORS' CONTRIBUTIONS AND CONFLICT OF INTEREST

Author Mohamad Amirul Hafiz Bin Md Shukri wrote the manuscript in consultation and supervision of authors Zulkiflee Abd Latif and Nurul Ain Mohd Zaki, who provided critical feedback and helped shape the research, analysis, and manuscript. All authors discussed the results and contributed to the final manuscript. Finally, the authors declare that there is no conflict of interest.

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